

FROM TARGETS AND TIMETABLES TO TECHNOLOGY INVESTMENTS

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Preface

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Abstract

This thesis aims to investigate the properties of self-enforcing International Environmental Agreements (IEAs) and the incentives to invest in R&D to develop a cost-reducing abatement technology. The analysis is based on a quadratic cost-benefit model introduced by Scott Barrett in 1994. I have extended the model to including investments in R&D. The countries in the model presented are symmetric with regards to costs and benefits of pollution abatement, but asymmetric with regards to the possibilities of investing in R&D. When assuming that one "enthusiastic" country invests in a technology that lowers the cost of pollution abatement for all countries, the result alters the grim picture that is painted in the literature on self-enforcing IEAs. By including the possibilities for strategic technology investments, the size of the stable IEA increases. So does the optimal level of abatement. Furthermore, global welfare increases. In the model outlined in this thesis, it leads to a Pareto-improvement in the welfare-level of the respective nations, including the enthusiastic country. The thesis thus concludes that future climate negotiations should put a heavier focus on the development and diffusion of technologies that lower the costs of reducing emissions, rather than strict emission reduction targets and binding timeframes.

1 Introduction

The UN initiated the first discussions on global warming in the 1980s. At the Rio Earth Summit in 1992, the UN Framework Convention on Climate Change (UNFCCC) came into place, which laid the foundation for the global climate negotiations as we know them today. The objective was the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1992, Article 2). The countries involved in the negotiations acknowledged that developed nations should contribute relatively more than developing nations to reducing the damages caused by climate change, since the main responsibility for the high levels of greenhouse gases (GHGs) in the atmosphere was due to the industrialization and economic growth in the developed part of the world. The cooperation should therefore be in accordance with the countries’ “common but differentiated responsibilities and respective capabilities” (UNFCCC, 1992, Article 3). It did not, however, specify any quantitative targets on emission reductions, which can explain why it was signed by so many countries (Barrett, 2003).

In 1997 the Kyoto Protocol was constructed, which introduced quantitative emissions reduction targets for 37 industrialized nations, referred to as Annex 1 countries. The protocol required the Annex 1 countries to cap their emissions of GHGs "at least 5 per cent below 1990 levels in the commitment period 2008 - 2012" (UNFCCC, 1998, Article 3). It also arranged for flexible mechanisms, such as quota trading, to enable the countries to reach their emission targets more cost-efficiently (Victor, 2004). However, the non-Annex 1 countries, mostly developing countries, were not subject to any emissions ceiling, and had therefore nothing to lose from signing the agreement (Barrett, 2003). A further target was agreed upon at the climate negotiations in Copenhagen in 2009. Here, the parties involved agreed to reduce global emissions so as to limit the increase in the average global temperature to 2 degrees above pre-industrial levels (UNFCCC, 2009). The target was, on the other hand, not backed by binding emission reduction plans and timeframes. Reducing emissions to the point of reaching the 2 degree goal will therefore be hard to fulfill under the current regime of climate negotiations (Victor, 2011).

Despite the fact that there are now 191 countries that have signed the Ky-

oto Protocol, the international climate negotiations are suffering from major structural challenges. There is still no global agreement on combating climate change and reduce emissions of GHGs. The United States failed to ratify the Kyoto Protocol in 2001. This was partly due the climate scepticism and opposition of the conservative movement in the country, and partly because the US would not accept mandatory reductions in GHG emissions without also imposing the same standards in developing countries (McCright and Dunlap, 2003). Canada followed by withdrawing from the agreement in 2011, arguing that "The Protocol only covers countries responsible for a small, and increasingly smaller, percentage of global emissions and, as a consequence, is not an effective vehicle for addressing the global challenge of climate change." ¹

An important obstacle to reaching a sustainable solution is thus that developing countries do not face binding emission targets. Major countries, like China and India, which are two of the top three GHG emitting countries along with the US, do not face any legally binding commitments. Emissions stemming from developing countries have been rising rapidly, and without deeper efforts by these countries, the shift towards a low-carbon world will be difficult (IEA, 2012). This concern is expressed by developed countries, which are willing to undergo further emission reductions if major developing economies increase their efforts. This was one of the reasons why the US did not ratify the Kyoto protocol, and the European Union (EU) is willing to increase their emission reduction targets towards 2020 if other major emitters do their fair share (Council of the EU: Presidency Conclusions 7224, 2007).

Slowing global warming requires large reductions in GHG emissions. Because CO₂ is a stock pollutant that mixes perfectly and has a long atmospheric lifetime, climate change is a global problem. The Stern Review from 2006 gave a thorough analysis of the economic costs and consequences of climate change. Some of the assumptions made in this report are, however, much debated. Especially the choice of how to evaluate the future, where Stern has chosen a low discount factor. Nordhaus (2007, chapter IX), for instance, has done similar calculations with a more conventional choice of discount factor, leading to less dramatic results. The Stern review does, however, give a picture of the importance of action towards climate change. According to the estimates in this

¹<http://www.ec.gc.ca/Publications/default.asp?lang=En&n=EE4F06AE-1&xml=EE4F06AE-13EF-453B-B633-FCB3BAECEB4F&offset=3&toc=show>

review, the cost of inaction is around 5 percent of global GDP every year, but uncertainty about the risks of climate change might increase this sum to be as large as 20 percent. On the other hand, Stern argues that the costs of reducing emissions to avoid the worst consequences of climate change can be limited to 1 percent of world GDP per year if starting now. Furthermore, combating climate change through reducing emissions also creates business opportunities through new markets related to low-carbon technologies, which is one of the four elements Stern suggests that a future climate framework should consist of. The other three are emission trading, action on reducing deforestation, and preparation for adaptation in countries that are vulnerable to climate change (Stern, 2006).

Regulations to avoid serious consequences from climate change requires international cooperation and coordination. Politically this means that no nation, acting alone, will have much impact on the possible solutions to the problem. Every country involved must have confidence that other countries are willing to make comparable efforts (Victor, 2011). Victor (2011) argues that the insufficient progress in finding sustainable solutions to the challenges of global warming first and foremost stems from the lack of a workable policy strategy. He claims that one of the main reasons is the way the current climate diplomacy is carried out, with a focus on strict emissions reduction targets and binding timeframes, and suggests that new approaches are needed. He argues that the focus should be driven away from "targets and timetables", and places a heavier weight on the importance of technology policies and smaller groups of cooperation in order to find a sustainable solution to one of the greatest challenges in history.

Barrett (2005) has another approach for explaining the challenges to finding a sustainable solution to the climate problem. His approach is that the current climate challenge can be regarded as a global governance problem where all countries share a global environmental resource - clean air, clean oceans etc. Collective wellbeing will increase if all countries cooperate in managing these resources, but every individual country will have an incentive to free-ride. Due to the free-rider problem, countries will have a motivation to develop institutions to increase cooperation in managing their shared environmental resource and thus increase collective welfare. One important feature of international agreements is, however, the principle of national sovereignty. Because of national sovereignty,

no supra-national power can enforce nations to comply with rules and regulations. National states choose independently whether to sign an agreement or not, and whether to withdraw from the agreement or remain a signatory. Since an agreement between nations cannot be legally binding, non-cooperative game theory is the proper tool for modelling International Environmental Agreements (IEAs).

As both Stern (2006) and Victor (2011) suggest, one important feature of future climate negotiations should be to develop low-carbon technologies. The purpose of this thesis is therefore to investigate how this can be implemented in a game-theoretical framework. The particular model I will use is the coalition model on IEAs introduced by Scott Barrett in 1994. Barrett's model is often cited in the literature of IEAs, and can be regarded as a benchmark model within this field. The model assumes symmetric nations, meaning that they have equal costs and benefits of pollution abatement, and the setup is a three-stage game. In stage one, the countries decide whether or not to join the coalition. In stage two, the signatory countries jointly decide their optimal level of pollution abatement by maximizing their collective net benefits of abatement, followed by the abatement decision of the singletons outside the coalition in stage 3, which maximize their individual net benefits of pollution abatement. Barrett (1994) argues that overcoming the free-rider problem is the main difficulty in constructing a functional climate coalition. When the gains to cooperation are large, the incentive to free-ride is large, and few countries will choose to sign the agreement. Conversely, when there is little to gain from cooperation, the incentive to free-ride is low, and a coalition is relatively easy to achieve. The climate challenge is clearly of the first kind, with large potential benefits from cooperation, resulting in a low number of signatories to the IEA. The model will be thoroughly explained in chapter 3.

I extend Barrett's model by introducing strategic investments in Research and Development (R&D) to develop a technology that reduces the cost of abatement for all countries. The point of departure is an "enthusiastic" country that acts as a frontrunner country with regards to investments in R&D. The term "enthusiastic" is inspired by Victor (2011), which uses the term to characterize countries with higher economic and administrative abilities. Here, it also expresses a country with a higher level of human capital, which is necessary to develop this cost-reducing technology. There is only one enthusiastic coun-

try, which can be thought of as the country with the lowest investment cost for developing a cost-reducing abatement technology. The questions to be investigated are, first, the incentives this country has to develop a cost-reducing technology. Second, how a lower cost of pollution abatement affects the optimal abatement levels in the respective countries, and finally, how this affects the size of the stable coalition. The analysis shows that a country that has the possibility to invest in a cost-reducing technology should, and will actually, do so. This will lead to a Pareto improvement in terms of increased welfare for all countries, including the investing country. There are two mechanisms leading to this result. A lower cost of pollution abatement will lead to a higher optimal level of abatement in all countries. It will further lead to increased cooperation, meaning that more countries will choose to maximize their collective payoff, rather than their individual net benefits of pollution abatement.

The theoretical expressions derived in this thesis are challenging to analyze. Therefore the main results arise in the numerical analysis, which is based on the numerical testing in Barrett (1994). In the model there are ten countries. These can be regarded as the ten major emitters of GHGs, but it can also picture the world as ten regions.

2 Literature Overview

The purpose of this thesis is not to do a literature search. However, it is useful to look at some studies within the scope of IEAs to understand some of the strengths and limitations of the model this thesis is based on, which is the one Barrett introduced in the paper "Self-Enforcing International Environmental Agreements" in 1994.

In the paper "International environmental agreements among asymmetric nations" by Matthew McGinty (2007), the main focus is on what he describes as "the convenient, but highly unrealistic assumption, that nations are identical" (McGinty, 2007, p. 45). He criticizes Barrett for having too pessimistic conclusions, on the basis that the free-rider problem increases as the gains from constructing an IEA rises. By including a trading scheme, based on permits, and the possibility that marginal benefits and costs may differ among countries, the results are altered. Permits allow the nations to meet their mitigation targets cost-efficiently. Through numerical simulations of 20 asymmetric nations he shows that an IEA can achieve substantial reductions in emissions, compared to the non-cooperative outcome, even when there are large gains from cooperation. These results are impossible when assuming symmetric countries and emphasizes the importance of transfers. Parts of the free-rider problem can therefore be overcome and a higher level of pollution abatement can be achieved by an IEA. The picture is thus not as grim as the one presented in Barrett (1994) when the assumption of symmetry among countries is relaxed. However, agreeing upon a transfer-system that satisfies all the countries involved in the negotiations will also create challenges, and limit the potential for finding a solution.

Barrett (2006) concludes pessimistically when analyzing "Climate Treaties and "Breakthrough" Technologies". He investigates an alternative treaty to the Kyoto Protocol which is presented as a system of two treaties. The focus in the first treaty is cooperative R&D on developing a breakthrough technology, while the other promotes collective adoption of this technology. The setup of the game is such that the R&D phase precedes the coalition formation. Then the signatory countries choose whether to adopt the technology, followed by the choice of adoption in the non-signatory countries. Two types of technologies are considered; a type Y technology, which generates zero-emissions, and a type X technology, which exhibits increasing returns to adoption, meaning that

the more countries adopt the technology, the higher will be the gain of implementing it. Once a certain amount of countries have adopted the technology, it will also be beneficial for the remaining countries to adopt it. He reaches the conclusion that breakthrough technologies will only be beneficial in the context of increasing returns, because otherwise the costs exceed the benefits, since the self-enforcing coalition usually consists of a low number of signatories. A treaty design that includes collective financing of R&D and adoption of the X-technology can thus sustain greater cooperation. However, the price to pay to increasing cooperation in these types of IEAs might be a system that is not cost-efficient, because in a world characterized by technological lock-in, it cannot be assumed that the markets choose the best technologies. Also, he concludes that a technology that satisfies the properties of the type X technology might not exist.

A similar analysis is done by Hoel and de Zeeuw (2010) that also investigate whether a focus on breakthrough technologies can improve the performance of IEAs. They introduce that the adoption cost of a technology vary with the level of R&D, and show that it might lead to a larger stable coalition and increased average welfare. There is a trade-off between R&D costs and adoption costs, meaning that the more is invested, the lower is the cost of implementing the technology. All countries are assumed identical. The decision of joining the coalition or not precede the choice of investments and adoption, and the R&D-costs are borne by the coalition, and not by an individual country. They show that cooperation is not a necessary condition for achieving sufficient R&D investments in technology development. However, a coalition may be necessary to prevent under- or overinvestments. The non-cooperative outcome may thus lead to a sufficiently high level of R&D, which is a public good, to induce full adoption of the technology. An IEA will, however, do better, since it can invest more to further lower the cost of adoption, or the treaty can prevent overinvestments in R&D. Finally, they conclude, with a more optimistic result than Barrett (2006), that IEAs can achieve more by focusing on R&D investments rather than emission reductions.

In a recent paper published by Johannes Urpelainen (2012) a game-theoretic model of strategic technology development is presented. The model is structured as a three-stage game. In stage one each country decides on technology development. In stage two, the countries that did not develop decide on adoption,

while the countries that did develop in stage one automatically adopt the technology. Finally, in stage three, all countries simultaneously decide on mitigation. Technology development and adoption thus precede the abatement decision. In the model, the cost of R&D varies across countries, and the cost of developing a technology that reduces the cost of mitigation is lowest in the frontrunner countries. Further, if the cost of adoption is relatively cheap, compared to the cost of R&D, strategic technology development will result in a large number of potential adopters. The analysis depends on two important conditions. First, some frontrunner countries must have low costs of developing the technology, and, second, a group of potential adopters must exist. If so, strategic technology development can lead to global diffusion and increased mitigation. The results thus suggest that strategic technology development by frontrunner countries might enable greater cooperation in combating climate change.

As expressed in the introduction, this thesis focuses on the incentives to invest in R&D to develop cost-reducing technologies and the effects this has on the coalition formation and the abatement decision of the respective countries. It does, in contrast to McGinty (2007), assume that the countries are symmetric with regards to costs and benefits of pollution abatement. A natural extension would be to include the possibility for asymmetries between countries. This is, however, not in the scope of this thesis. In contrast to Barrett (2006), Hoel and de Zeeuw (2010) and Urpelainen (2012), there is only one country that invests in R&D to develop a cost-reducing abatement technology in the model presented in this thesis. Also, the investment decision precedes the coalition formation. In this way, the pure effects of a lower cost of abatement are revealed. All countries are also assumed to adopt the cost-reducing abatement technology before the choice of whether or not to join the coalition, and there are no cost of adoption included in the model. The investment cost is borne by one country, and the analysis shows that if a country has the possibility to develop this cost-reducing abatement technology it will actually do so, because it will pay off in a higher net benefit for all countries, including the country that bears the investment costs. This is due to two effects. First, the optimal abatement level will increase for all countries. Second, the stable coalition will expand, meaning that more countries will maximize joint net benefits rather than their individual net benefits of pollution abatement. The model will be thoroughly explained below.

3 A Model of an International Environmental Agreement

The model I will use as a basis for my analysis throughout this Master thesis is based on the one Scott Barrett develops in the paper “Self-Enforcing International Environmental Agreements” (1994). The model is one in which the number of signatories, the terms of the agreement and the actions of the non-signatory countries are all determined endogenously. The decisions can be regarded as taken by representatives acting like social planners for each country (Finus, 2008). Signatory countries will maximize their collective net benefits of pollution abatement, while non-signatory countries each maximize their individual payoff of pollution abatement.

There are $i \in \{1, \dots, N\}$ symmetric countries, all of which have an increasing and concave benefit-function of pollution abatement and an increasing convex cost-function of abatement. Each country’s net benefit function is known by all countries. The choice-variable is restricted to pollution abatement, with Q defined as global abatement, where $Q = \sum_i q_i$, and q_i is the abatement of country i . A country i earns benefit from its own abatement, but also from the pollution abatement undertaken by the other countries (Barrett, 1994).

The benefit-function of country i is defined as

$$B_i(Q) = \frac{b}{N} \left(aQ - \frac{Q^2}{2} \right) \quad (1)$$

where $B'(Q) > 0$ for $a > Q$ and $B'(Q) < 0$ for $a < Q$. The parameter a defines the level of abatement at which the benefit is largest, or where the marginal-benefit goes from being positive to negative. $B''(Q) < 0$ for all Q , so the benefit is a decreasing function of the abatement-level. The benefit-function is thus only meaningful for values of $Q < a$. The parameter b is a multiplier, saying something about the size of the benefit as such. The higher is b the larger is the benefit from abatement.

The cost-function of each country i is

$$C_i(q_i) = \frac{cq_i^2}{2} \quad (2)$$

which is an increasing convex function of the abatement-level. The more a country abates its emissions, the more expensive it becomes to increase the level of abatement by one unit, so $C'_i(q_i) > 0$, $C''_i(q_i) > 0$. The parameter c gives the slope of each country's marginal cost curve.

3.1 Benchmarks: No Cooperation and Full Cooperation

Before analyzing the equilibrium of the model, the non-cooperative and full cooperative outcomes will be evaluated. These are useful benchmarks to consider the limitations and possibilities from creating IEAs.

3.1.1 Non-Cooperative Outcome

The non-cooperative solution can be regarded as the benchmark for the worst-case scenario, where the countries fail to reach an agreement on reducing emissions of GHGs. In the non-cooperative case every individual country maximizes its own net benefit of pollution abatement, not taking into account that their level of abatement affects the other countries' welfare positively. Every individual country i thus maximizes their individual payoff, solving the following maximization problem:

$$\max_{q_i} \left\{ \frac{b}{N} \left(a \sum_i q_i - \frac{1}{2} \left(\sum_i q_i \right)^2 \right) - \frac{1}{2} c q_i^2 \right\} \quad (3)$$

The first order condition for this maximization problem is

$$\frac{ba}{N} - \frac{b \sum q_i}{N} - c q_i = 0 \quad (4)$$

Since all countries are assumed identical ($q_i = q_j$), the optimal non-cooperative abatement level for an individual country i is

$$q_0 = \frac{a}{N(1 + \frac{c}{b})} \quad (5)$$

The global optimal non-cooperative level of abatement will be the sum of every individual country's optimal level, $Q_0 = N q_0$:

$$Q_0 = \frac{a}{(1 + \frac{c}{b})} \quad (6)$$

The marginal benefit of the first unit of pollution abatement in the non-cooperative outcome is $\frac{ab}{N}$, which is where the marginal benefit curve crosses the vertical axis in figure 1. The marginal benefit of the ath unit is zero, which is where the marginal benefit curve of the non-cooperative outcome crosses the horizontal axis in figure 1. The non-cooperative level of pollution abatement depends positively on the parameters a and b , and negatively on the marginal abatement cost c , meaning that $\partial Q_0/\partial a > 0$, $\partial Q_0/\partial b > 0$, $\partial Q_0/\partial c < 0$. So if a increases, the peak of the benefit-function moves to the right, triggering the optimal abatement-level to increase. If b increases, the benefit of abatement increases for all levels of abatement, which also yields a higher optimal level of abatement, everything else equal. If the cost of abatement increases, the net benefit of abatement decreases, resulting in a lower optimal level of abatement.

3.1.2 Full Cooperative Outcome

The full cooperative outcome, which is what the countries should aim for, is such that joint welfare is maximized, and every individual country i abates its emissions of GHGs at the level which is collectively optimal. The full cooperative outcome is found by maximizing joint net benefits of pollution abatement, solving the following maximization problem:

$$\max_{q_i} \left\{ \frac{b}{N} (aNq_i - \frac{1}{2}(Nq_i)^2) - \frac{1}{2}cq_i^2 \right\} \quad (7)$$

Each country thus takes into account the benefits of its abatement on all the other countries. The first order condition of the above maximization problem is:

$$ba - bNq_i - cq_i = 0 \quad (8)$$

The optimal abatement level for an individual country i under full cooperation, with $q_i = q_j$, will thus be

$$q_c = \frac{a}{(N + \frac{c}{b})} \quad (9)$$

giving an aggregated optimal full cooperative level of abatement equal to $Q_c = Nq_c$:

$$Q_c = \frac{aN}{(N + \frac{c}{b})} \quad (10)$$

In the full cooperative outcome, the marginal benefit of the first unit of pollution abatement is equal to ab , which is where the marginal benefit curve crosses the vertical axis in figure 1. As in the non-cooperative outcome the marginal benefit of the ath unit is equal to zero. We easily see that also the full cooperative level of abatement depends positively on a and b and negatively on c , hence $\partial Q_c / \partial a > 0$, $\partial Q_c / \partial b > 0$, $\partial Q_c / \partial c < 0$.

As expected, the global optimal full cooperative level of abatement is larger than the global optimal non-cooperative level of abatement, $Q_c > Q_0$, as shown in figure 1. If all countries set the full cooperative abatement level they will be better off compared to if they all set the non-cooperative abatement level. This will become clear in the numerical example in chapter 3.4.

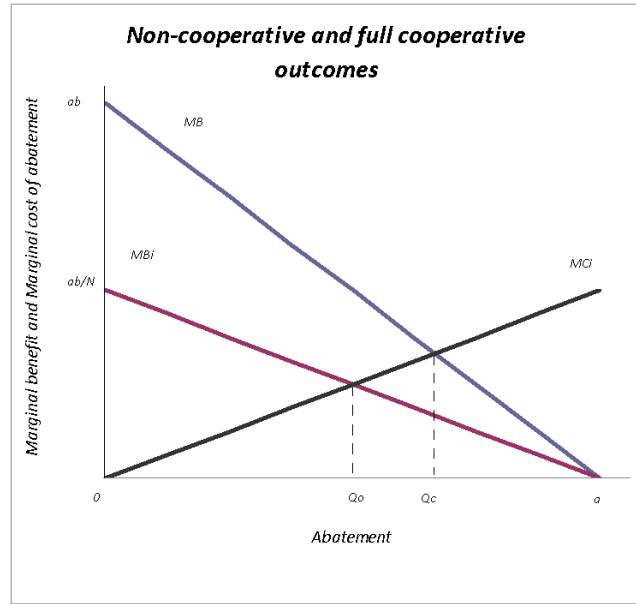


Figure 1: This figure illustrates the two benchmark cases - the abatement level in the full cooperative and non-cooperative outcomes.

The result of international negotiations on environmental problems is, however, not limited to full cooperation or no cooperation. Partial cooperation is also a possible, and probably, more realistic outcome. However, this equilibrium is incomplete, meaning that the countries would do better if all countries cooperated. In this sense, a self-enforcing IEA can be compared to a Prisoner's dilemma game, because the full cooperative equilibrium is usually not stable, as will be shown in the following sections (Perman et al, 2011).

3.2 Self-Enforcing IEAs

The N countries in the model all suffer from a common externality problem, which is GHG emissions, and are thus potential signatories to an IEA on pollution abatement. The outcome of an international treaty on climate improvement is a public good, which then also gives an incentive for free-riding. Countries that do not sign the agreement benefit from the pollution abatement undertaken by the signatory countries, without bearing the costs. There are two types of free-riding: not to participate in the IEA, and not to comply with the obligations agreed upon in the agreement (Finus, 2008).

First, the countries must choose whether or not to sign the agreement. Then, the countries decide upon the terms of the IEA. These will consist of a set of pollution abatement levels undertaken by the signatory countries, depending on how many countries that choose to sign the agreement (Perman et al, 2011).

The terms of the agreement are such that the optimal level of abatement in the signatory countries is derived by maximizing the coalition's joint net benefit of pollution abatement, while a non-signatory maximizes the country's individual payoff function. The decision of joining the coalition or not is hence a choice of which objective function to maximize, which lead to different optimal levels of abatement. The coalition acts as a single player, while the non-signatory countries act as singletons. The countries can thus be regarded as symmetric *ex-ante*, with regards to costs and benefits of pollution abatement. However, *ex-post*, the countries receive different payoffs depending on if they choose to enter the agreement or not (Finus, 2008).

If an additional country decides to accede to the treaty, the number of signatory countries will increase, and thus also the signatories' abatement level. Conversely, if a country withdraws from the agreement, there will be a lower number of signatories, and the optimal decision for the signatory countries, which maximize the coalition's collective net benefits of pollution abatement, is to lower their level of abatement. These constitute a set of penalties and rewards reflecting the signatory countries' abatement decision as a function of the number of countries signing the treaty (Perman et al, 2011).

If the terms of the IEA gives incentives for the N countries, both the signatory- and the non-signatory countries, to hold on to their decision once the agreement has come into place, the treaty is self-enforcing. A self-enforcing agreement must be renegotiation proof, meaning that there is no incentive to renegotiate the agreement once it has come into place. The second type of free-riding, namely not to comply with the obligations of the agreement, is hence absent in a self-enforcing IEA. This is why the full cooperative outcome is usually not stable, since one or more countries will gain a higher payoff by withdrawing from the agreement compared to the payoff they earn by remaining a signatory (Perman et al, 2011).

An IEA is self-enforcing if the conditions of internal and external stability are met. The coalition is internally stable if no signatory country can gain a higher payoff by unilaterally leaving the coalition, and externally stable if no non-signatory can earn a higher payoff by acceding to the agreement. These payoff functions will be derived in the following chapter. Letting π_s and π_n denote the payoff for the signatory and non-signatory countries respectively, and defining the share of countries signing the IEA as α , the payoffs, π_s and π_n , will be functions of α . The coalition consisting of αN countries is self-enforcing if (Barrett, 1994)

$$\pi_n(\alpha - \frac{1}{N}) \leq \pi_s(\alpha) \quad (11)$$

and

$$\pi_n(\alpha) \geq \pi_s(\alpha + \frac{1}{N}) \quad (12)$$

In open membership games like the Kyoto-agreement, where all nations can join the IEA, both the above equations must be satisfied. It might, however, be

such that the agreement is exclusive, and existing members can block the entry of new members. If so, only the internal stability condition must be satisfied (McGinty, 2007).

Self-enforcing IEAs typically exist of a relatively small number of countries, giving little improvement compared to the non-cooperative case. Barrett (2003) argues that when the gains to cooperation are small, meaning that the difference between global net benefits of pollution abatement under the non-cooperative and full cooperative outcome is small, an IEA may achieve a high degree of cooperation. However, the larger the benefits from joining the IEA, the lower will be the participation level. Furthermore, a self-enforcing IEA can consist of many signatories, if only the cost-benefit ratio, $\frac{c}{b}$, is small. Barrett (1994) demonstrates that if $\frac{c}{b}$ is small, the difference between global net benefits under the full cooperative and non-cooperative outcomes will also be small, meaning that IEAs signed by many countries do not increase global net benefits by much, compared to the non-cooperative outcome. The gains to free-riding are therefore also small. In figure 1 this can be regarded as if the marginal cost curve was relatively flat. This suggests that IEAs signed by a large number of countries do only have marginal effects. If the cost-benefit ratio, $\frac{c}{b}$, is large, the marginal cost curve in figure 1 will be steep, and the difference between global net benefits under the full cooperative and non-cooperative outcomes will be large. In this case, there is more to gain by free-riding, and less countries will choose to sign the agreement on reducing their emissions of GHGs, even though the gains from full cooperation are larger. How much an IEA may improve on the non-cooperative outcome in this model depends crucially the parameter values. This will be analyzed more in detail in the numerical examples throughout this thesis.

Global warming is a challenge for which the benefits from cooperation are substantial. Also the costs are large, so one can regard the parameter values b and c as large, as well as the number of countries, N . Barrett (1994) argues that when both b and c are large, the difference between net benefits under full cooperation compared to the non-cooperative solution is large. However, few countries will then choose to sign the agreement. This is bad news for the environment, since the problems the world faces today is a challenge for which global participation is necessary to be able to reach a sustainable solution.

3.3 Modelling the Self-Enforcing IEA

The share of countries signing the IEA is defined as α , meaning that there are αN signatory countries and $(1 - \alpha)N$ non-signatory countries. Subscript n expresses non-signatory countries, while subscript s denotes signatory countries' behavior. Since the countries are symmetric, aggregated abatement of non-signatory countries will be $Q_n = (1 - \alpha)Nq_n$, and likewise for signatory countries; $Q_s = \alpha Nq_s$. The decisions are made sequentially, and there are three stages in the game:

Stage 1: The countries decide whether or not to join the agreement.

Stage 2: The signatory countries choose their optimal level of abatement by maximizing their aggregate net benefits of pollution abatement.

Stage 3: The non-signatories choose their optimal level of abatement by maximizing their individual net benefits of abatement.

Barrett (1994) models the IEA as a stage game, where decisions are made sequentially. The signatory countries act as Stackelberg leaders making the first move, followed by the move of the non-signatories. The choices made are, however, inter-dependent, meaning that the signatory countries will take into account how the non-signatories will react when making their first move (Barrett, 2005). The game is solved by using backward induction, starting by solving for stage three. This will give the non-signatories' optimal abatement level for any level of pollution abatement in the signatory countries. Hence, the strategic reaction of the outsiders is taken into account when the coalition chooses its optimal abatement level in the second stage (Finus, 2008). A non-signatory country will thus

$$\max_{q_n} \left\{ \frac{b}{N} (aQ - \frac{1}{2}Q^2) - \frac{1}{2}cq_n^2 \right\} \quad (13)$$

The first order condition of this maximization problem is

$$\frac{b}{N} (a - Q) - cq_n = 0 \quad (14)$$

which further, by inserting for $Q = Q_s + Q_n$, can be written as

$$a - Q_s - Q_n = \frac{Ncq_n}{b} \quad (15)$$

With $q_n = \frac{Q_n}{(1-\alpha)N}$, the best response function for the non-signatory countries, given the abatement undertaken by the signatories, is

$$Q_n(\alpha, Q_s) = \frac{(1-\alpha)(a - Q_s)}{(\frac{c}{b} + 1 - \alpha)} \quad (16)$$

From this best response function we see that the optimal level of abatement in the non-signatory countries depends negatively on the level of abatement in the signatory countries, so $\frac{\partial Q_n}{\partial Q_s} < 0$. The higher the signatory countries set their level of abatement, the lower will be the level of abatement in the non-signatory countries. The signatory countries takes this into account when deciding their optimal level of abatement in the second stage. This implies that a degree of carbon leakage is internalized in this model, since it is modelled as a Stackelberg game and not as a Nash equilibrium (Finus, 2008).

The signatory countries maximize their collective net benefits, subject to equation (16). The abatement decision for a signatory country is hence found by solving the following maximization problem:

$$\max_{q_s} \left\{ \alpha N \frac{b}{N} \left[a(Q_s + Q_n(Q_s)) - \frac{1}{2}(Q_s + Q_n(Q_s))^2 \right] - \alpha N \frac{1}{2} c q_s^2 \right\} \quad (17)$$

The corresponding first order condition is

$$\frac{b}{N} \left[a \left(\frac{dQ_s}{dq_s} + \frac{\partial Q_n}{\partial Q_s} \frac{dQ_s}{dq_s} \right) - (Q_s + Q_n(Q_s)) \left(\frac{dQ_s}{dq_s} + \frac{\partial Q_n}{\partial Q_s} \frac{dQ_s}{dq_s} \right) \right] - c q_s = 0 \quad (18)$$

Inserting the explicit functions of the derivatives, and $q_s = \frac{Q_s}{\alpha N}$, with q_s identical for all the coalition-members, the optimal abatement level for the coalition is

$$Q_s^*(\alpha) = \frac{\frac{aca^2N}{b}}{\frac{\alpha^2 Nc}{b} + (\frac{c}{b} + 1 - \alpha)^2} \quad (19)$$

Inserting equation (19) into (16) gives the optimal level of abatement in the non-signatory countries:

$$Q_n^*(\alpha) = \frac{a(1-\alpha)(\frac{c}{b} + 1 - \alpha)}{\frac{\alpha^2 Nc}{b} + (\frac{c}{b} + 1 - \alpha)^2} \quad (20)$$

Equation (19) and (20) give the subgame perfect Nash equilibrium abatement-levels, meaning the abatement profile that serves both types of countries best, given the strategy of the other type of countries.

If an additional country joins the IEA, increasing αN , the optimal behavior of the signatory countries is to increase their total abatement-level. This can be shown by differentiating Q_s with respect to α :

$$\frac{\partial Q_s}{\partial \alpha} = \frac{\frac{2a\alpha Nc}{b} \left(\frac{c}{b} + 1 - \alpha\right) \left(\frac{c}{b} + 1\right)}{\left[\frac{\alpha^2 Nc}{b} + \left(\frac{c}{b} + 1 - \alpha\right)^2\right]^2} > 0 \quad (21)$$

Conversely, if a country withdraws from the IEA, the optimal policy for the remaining signatories is to reduce their abatement-level, which also means that the non-signatories will increase their abatement level:

$$\frac{\partial Q_n}{\partial \alpha} = \frac{-\frac{ac}{b} \left[\left(\frac{c}{b} + 1 - \alpha\right)^2 + \alpha N \left(2\left(\frac{c}{b} + 1 - \alpha\right) - \frac{\alpha c}{b}\right)\right]}{\left[\frac{\alpha^2 Nc}{b} + \left(\frac{c}{b} + 1 - \alpha\right)^2\right]^2} < 0 \quad (22)$$

Since the terms of the agreement are that the coalition always maximizes the collective net benefits of pollution abatement, the optimal response for the coalition when a country withdraws is to lower their level of abatement, since there are now less signatories to the IEA, which is shown analytically in equation (21), with $\frac{\partial Q_s}{\partial \alpha} > 0$. The optimal response for the non-signatory countries is then to increase their level of pollution abatement, $\frac{\partial Q_n}{\partial \alpha} < 0$. This can be regarded as a credible punishment for the country that leaves the coalition, since the gains from free-riding then are reduced.

3.4 Numerical Example

Barrett (1994), gives a numerical example to better understand the concept of a self-enforcing IEA. He chooses the following parameter values; $a=100$, $b=1$, $c=0,25$ and $N=10$, and shows that the only stable coalition consists of four countries, namely that $\alpha = 0,4$. For $\alpha = 0,4$, both the internal- and external stability conditions are met, meaning that $\pi_n(\alpha - \frac{1}{N}) \leq \pi_s(\alpha)$ and $\pi_n(\alpha) \geq$

α	q_s	q_n	π_s	π_n	Q	Π
0	-	8,0	-	472,0	80,0	4720,0
0,1	1,9	8,5	476,8	468,1	78,7	4690,0
0,2	4,2	8,7	474,0	466,6	78,2	4681,2
0,3	6,7	8,4	472,3	468,9	78,9	4699,4
0,4	8,9	7,6	472,2	474,9	81,1	4738,1
0,5	10,5	6,3	473,7	482,5	84,2	4781,2
0,6	11,3	4,9	476,4	489,4	87,7	4815,9
0,7	11,5	3,6	479,5	494,3	91,0	4839,8
0,8	11,1	2,5	482,7	497,3	93,8	4855,9
0,9	10,5	1,6	485,4	498,8	95,9	4867,9
1	9,8	-	487,8	-	97,6	4878,0

Table 1: The table shows the relationship between the size of the coalition, the optimal levels of abatement and the welfare levels.

$\pi_s(\alpha + \frac{1}{N})$. Non-signatories hence earn a greater payoff by entering the coalition whenever $\alpha < 0, 4$, and signatories do better by withdrawing from the agreement whenever $\alpha > 0, 4$. The results are shown in table 1.

Even though the decision of joining the coalition is a one-shot decision, it is helpful, for understanding the mechanism, to think of it sequentially. The results are outlined in table 2. Suppose that initially one country decides to join the coalition. Then, the next country can choose between signing the IEA and get payoff $\pi_s(\alpha = 0, 2) = 474$ or not to sign, and get payoff $\pi_n(\alpha = 0, 1) = 468, 1$. This country will choose the higher payoff and therefore choose to sign the IEA. The third country can now choose between joining the coalition, increasing the size of the coalition to three countries, and get payoff $\pi_s(\alpha = 0, 3) = 472, 3$, or not signing and get payoff $\pi_n(\alpha = 0, 2) = 466, 6$. Again, the country will choose to sign, since $\pi_s(\alpha = 0, 3) > \pi_n(\alpha = 0, 2)$. Further, the fourth country can choose to sign the agreement and get payoff $\pi_s(\alpha = 0, 4) = 472, 2$ or not to and get payoff $\pi_n(\alpha = 0, 3) = 468, 9$. Again, signing the agreement, increasing the size of the coalition to four countries, gives the country higher payoff compared to not signing. The fifth country, however, has the choice between acceding the agreement and earn a payoff of $\pi_s(\alpha = 0, 5) = 473, 7$ and not acceding and earn a payoff of $\pi_n(\alpha = 0, 4) = 474, 9$. This country will hence not accede to the agreement, since $\pi_s(\alpha = 0, 5) < \pi_n(\alpha = 0, 4)$. The same will be the case for the last five countries, that will choose not to sign, since the payoff of remaining a non-signatory, when there are already four signatory countries to the agreement,

α	$\pi_n(\alpha)$	$\pi_s(\alpha + \frac{1}{N})$	$\pi_n(\alpha - \frac{1}{N})$	$\pi_s(\alpha)$
0	472,0	-	476,6	-
0,1	468,1	474,0	472,0	476,8
0,2	466,6	472,3	468,1	474,0
0,3	468,9	472,2	466,6	472,3
0,4	474,9	473,7	468,9	472,2
0,5	482,5	476,4	474,9	473,7
0,6	489,4	479,5	482,5	476,4
0,7	494,3	482,7	489,4	479,5
0,8	497,3	485,4	494,3	482,7
0,9	498,8	487,8	497,3	485,4
1	-	489,7	-	487,8

Table 2: The table shows the calculations of the internal and external stability conditions.

yields a higher payoff than acceding the treaty and maximize aggregate payoff.

The same logic can be applied in the reversed case, with the full cooperative case as the point of departure, following the two last columns in table 2. If one country initially withdraws from the agreement, the next country has the choice between remaining a signatory and earn payoff $\pi_s(\alpha = 0, 9) = 485, 4$, or to withdraw from the agreement and get payoff $\pi_n(\alpha = 0, 8) = 497, 3$. It will thus withdraw, since the payoff from leaving the agreement and pursue its individually rational policy, is greater than the payoff it earns by remaining a signatory and maximize the coalition's aggregated net benefits. This will be the case until six countries have withdrawn from the agreement. When the coalition is made up of four countries, a remaining signatory has the choice between staying in the coalition and earn payoff $\pi_s(\alpha = 0, 4) = 472, 2$, or withdrawing and earn payoff $\pi_n(\alpha = 0, 3) = 468, 9$. The country will then remain a signatory, since $\pi_s(\alpha = 0, 4) > \pi_n(\alpha = 0, 3)$.

Hence, the self-enforcing IEA does, with the above parameter values, consist of four countries. We see, from table 1, that the global net benefits, defined as $\Pi = \alpha N \pi_s + (1 - \alpha) N \pi_n$ increase as the size of the coalition increases, but that the IEA consisting of four countries is the only stable IEA.

Testing this with lower abatement costs, all other parameter values equal, I find that the stable coalition increases when c decreases. When c decreases, the cost-benefit ratio $\frac{c}{b}$ becomes smaller, and the difference between global net

c	α	Q	Π
0,25	0,4	81,1	4738,1
0,15	0,5	87,8	4867,2
0,1	0,6	91,8	4910,6
0,05	0,8	96,7	4970,7

Table 3: As the cost-parameter, c , declines, the stable coalition expands. Aggregated abatement and welfare increase.

benefits under the non-cooperative and full cooperative outcome decreases. As stated earlier, the IEA then achieves a higher degree of cooperation. With $c = 0,15$, the stable size of the coalition increases to five countries. If $c = 0,1$, the stable coalition consists of six countries, and if c is 0,05, the stable coalition-size increases to eight countries. The total world welfare thus increases as c decreases. Table 3 shows how the stable size of the coalition, the total pollution abatement and the total welfare increase as c declines. This is obviously because the cost of pollution abatement is lower for all countries, but also because more pollution abatement is undertaken as the size of the stable coalition increases, since more countries maximize joint welfare. This relationship between the cost-parameter, c , and the stable size of the coalition is presented graphically in figure 2.

If the cost of abatement decreases, the size of the stable coalition will increase, and the agreement can achieve more relative to the initial situation with a higher cost of abatement. However, for this to be the case, one or more countries must be willing to invest in a technology that lowers the cost of abatement for all countries. This is not analyzed before and will be elaborated in the following chapter.

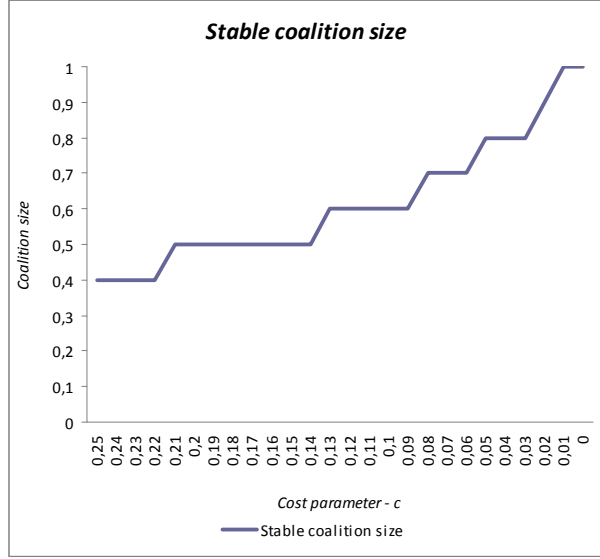


Figure 2: The size of the stable coalition increases as the cost of abatement, c , declines, all other parameter values equal.

4 An Enthusiastic Investment

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol emphasize that developed countries should contribute more than developing countries in combating climate change. The developed countries are, to a large extent, responsible for the current high levels of GHGs in the atmosphere after more than 150 years of industrial activity, followed by corresponding economic growth. The UNFCCC thus places a heavier burden on industrialized nations under the principle "common but differentiated responsibilities and respective capabilities" (UNFCCC, 1992, Article 3).

Victor (2011) divides the world into two subgroups of countries. The first consists of enthusiastic countries, which are willing and able to spend their own resources on combating climate change. The other group, the reluctant countries, have different priorities and less developed administrative systems to control polluting activities. Building on this further, one can regard several developed nations, in particular European and Scandinavian countries, as frontrunners, belonging to the group Victor (2011) names enthusiastic countries.

These are in a unique position both economically and with regards to human capital to engender a sustainable solution when it comes to carbon emissions, which also brings about a moral obligation to lead by example in this area.

It is understood that GHG emissions could be reduced by lowering production and therefore economic growth. This is highly undesirable. However, lower growth may not be a necessary condition for a more responsible level of GHG emissions. More efficient production, realized through an improvement in technology, could facilitate current or even elevated levels of economic growth, while keeping emissions stable or even driving them lower.

Even though the countries in the model presented in this thesis are symmetric with regards to costs and benefits of pollution abatement, I will base the further analysis on the assumption that they are asymmetric in their ability to invest in R&D. This asymmetry can be regarded as, for instance, a different historical focus on educational policies, which have led to lower costs of technology development in some countries. The costs of developing cost reducing technologies are thus prohibitively high in the countries which lack this historical emphasis on education. I will use the argument above - that developed nations should contribute more than developing ones - to motivate the further analysis. The focus will be on strategic R&D investments to promote a low cost abatement technology.

Suppose that a country invests in a technology that lowers the cost of abatement for all countries. This country, which I will call the "enthusiastic country", has the possibility to invest to "save for all". Victor (2011) uses the term "enthusiastic" to describing a country with higher economic and administrative capacity. Here, the term "enthusiastic" is also a result of a historically larger focus on education, research and development, leading to a higher level of human capital.

In this model, there is only one "enthusiastic" country, which can be regarded as the country with the lowest technology development cost, and hence the strongest incentive to invest. Assuming that this country is a developed country, with a moral obligation to contribute to solving the climate threat, it will not impose any intellectual property rights (IPR) on the innovation, and the technology is free to acquire for the remaining countries.

The enthusiastic country is not willing to develop a cost reducing technology if it does not lead to implementation in the other countries. This sheds light on the importance of the strategic effects of technology development. Further, this can be regarded as the "common but differentiated responsibilities" expressed in the UNFCCC. The enthusiastic country has the possibility, and hence a responsibility, to invest to "save for all", but the remaining countries then have the responsibility of implementing the technology. So, either we have an equilibrium such that no development occurs, or an equilibrium where the technology is developed and implemented by all countries.

Also, if the enthusiastic country invests, it will also participate in the coalition. This supports the notion "enthusiastic", because not only will the country invest in R&D and develop the cost reducing technology, it also knows at this stage that it will be a signatory to the IEA, maximizing the coalition's joint payoff rather than its individual net benefits of pollution abatement.

The further analysis is thus based on two key assumptions. First, one frontrunner country must have the possibility and willingness to develop a technology that reduces the cost of pollution abatement. Second, this technology will be free to acquire for the rest of the world, and all countries will therefore adopt and implement this cost-reducing technology.

One necessary condition, which will be proved to be satisfied, is that both developers and adopters must benefit from the development of the technology. Since there are no prices included in this model, the adopters naturally benefit from lower abatement costs. However, as will be shown, also the enthusiastic country will earn higher net benefits from the development of the cost-reducing technology. There are two reasons for this. First, the costs of pollution abatement will be lower. Second, the strategic effects - that all other countries will undertake more pollution abatement, and more countries will maximize the coalitions objective function - will lead to greater benefits for all the countries, also the enthusiastic.

The structure of the game is such that the R&D phase and the adoption of the new technology precede the coalition formation. The enthusiastic country knows at this point that it will be a signatory to the IEA. It has the same benefit and cost-functions as the other countries, but has more knowledge, which leads it to develop this cost-reducing technology. After making this technological

leap, the corresponding technology and know how are free to acquire, and other countries will copy and implement it. The outline of the game is thus as follows:

Stage 0: The enthusiastic country invests in a technology that lowers the cost of abatement for all countries. All countries adopt and implement the technology.

Stage 1: The countries decide whether or not to join the agreement.

Stage 2: The signatory countries choose their optimal level of abatement by maximizing their aggregate net benefits of pollution abatement.

Stage 3: The non-signatories choose their optimal level of abatement by maximizing their individual net benefits of abatement.

The question then becomes; how will this alter the abatement and welfare levels, along with the stable coalition size.

4.1 The Effects of a Lower Cost of Abatement

4.1.1 Full Cooperative Case

We already know that in the full-cooperative solution, with $\alpha = 1$, a lower cost of abatement, c , will result in a higher optimal abatement-level. Differentiating equation (10) with respect to c gives:

$$\frac{\partial Q_c}{\partial c} = \frac{-\frac{Na}{b}}{\left(N + \frac{c}{b}\right)^2} < 0 \quad (23)$$

An investment in a technology that lowers the unit cost of abatement, will consequently pay off in higher abatement-levels in the full-cooperative case. The total world welfare in the full cooperative case is

$$\Pi_c = N\pi_c = N\frac{b}{N} \left(aQ_c - \frac{1}{2}Q_c^2 \right) - N\frac{1}{2}cq_c^2 \quad (24)$$

Differentiating this with respect to c yields:

$$\frac{\partial \Pi_c}{\partial c} = \frac{-a^2N}{2\left(N + \frac{c}{b}\right)^2} < 0 \quad (25)$$

meaning that, when the countries are faced with a lower cost of abatement, the total welfare will increase.

4.1.2 Non-Cooperative Case

Also in the non-cooperative outcome, $\alpha = 0$, where the optimal abatement level is as in equation (6), and all countries maximize individual net benefit, a lower cost of abatement will increase the optimal non-cooperative abatement level:

$$\frac{\partial Q_0}{\partial c} = \frac{-\frac{a}{b}}{\left(1 + \frac{c}{b}\right)^2} < 0 \quad (26)$$

Looking at the total welfare in this case with

$$\Pi_0 = N\pi_0 = N\frac{b}{N} \left(aQ_0 - \frac{1}{2}Q_0^2 \right) - N\frac{1}{2}cq_0^2 \quad (27)$$

and differentiating this with respect to c gives:

$$\frac{\partial \Pi_0}{\partial c} = \frac{-a^2 \left[\frac{c}{b}(2N-1) + 1 \right]}{2N \left(1 + \frac{c}{b} \right)^3} < 0 \quad (28)$$

which is also negative, meaning that also in worst case scenario, where there are no signatories to the agreement, the welfare will increase if the cost of abatement is reduced.

An investment in a technology that lowers the unit cost of abatement, will hence pay off in higher abatement levels in both the non-cooperative and the full cooperative case. Also the global welfare level will increase when the cost of abatement decreases in these two benchmark cases. Developing the new technology, on the other hand, has a cost which must be born solely by the enthusiastic country.

4.1.3 The Self-Enforcing IEA

Now, let's consider how a lower cost of abatement impacts the abatement-levels for the signatory and the non-signatory countries when the unit cost of abatement decreases in the more realistic case, where there are some countries that

are signatories to the IEA and other countries remain outside. Here I will look at the effects for a given size of the coalition.

The optimal levels of abatement in the coalition, Q_s , and the non-signatory countries, Q_n , are in the subgame perfect Nash equilibrium according to equation (19) and (20), respectively. Differentiating (19) with respect to the cost-parameter, c , for a given size of the coalition gives:

$$\frac{\partial Q_s}{\partial c} = \frac{\frac{a\alpha^2 N}{b} \left[\left(\frac{c}{b} + 1 - \alpha \right) (1 - \alpha - \frac{c}{b}) \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 N c}{b} \right]^2} \quad (29)$$

which is positive for $\alpha + \frac{c}{b} > 1$, and negative for $\alpha + \frac{c}{b} < 1$, meaning that when the cost decreases below a certain level, for a given b , the coalition will decrease their level of abatement when the cost of abatement declines. With the parameter values used in this thesis, which will be analyzed numerically in chapter 4.3, the sign of the above equation will always be negative, as long as the size of the stable coalition is unchanged. This is due to the fact that the non-signatory countries will increase their optimal level of abatement as the cost decreases for a given size on the stable coalition, which will be showed below. The optimal decision for the signatory countries is hence to lower their level of abatement, as long as the coalition size remains unchanged.

The result for a single coalition member, knowing that

$Q_s = \alpha N q_s$, is:

$$q_s^*(\alpha, c) = \frac{\frac{a\alpha c}{b}}{\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 N c}{b}} \quad (30)$$

with

$$\frac{\partial q_s}{\partial c} = \frac{\frac{a\alpha}{b} \left[\left(\frac{c}{b} + 1 - \alpha \right) (1 - \alpha - \frac{c}{b}) \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 N c}{b} \right]^2} \quad (31)$$

which gives a similar result as above.

The non-signatories will, however, for a given size of the coalition, increase their abatement-level when the cost of abatement decreases. Differentiating (20) with respect to c yields:

$$\frac{\partial Q_n}{\partial c} = \frac{-\frac{a}{b}(1 - \alpha) \left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \alpha^2 N (1 - \alpha) \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \alpha^2 N \frac{c}{b} \right]^2} < 0 \quad (32)$$

Looking at every single non-signatory, with $Q_n = (1 - \alpha)Nq_n$:

$$q_n(c) = \frac{\frac{a}{N}(\frac{c}{b} + 1 - \alpha)}{(\frac{c}{b} + 1 - \alpha)^2 + \alpha^2 N \frac{c}{b}} \quad (33)$$

the result for a single non-signatory country of a lower cost of pollution abatement, for a given size of the stable coalition, is:

$$\frac{\partial q_n}{\partial c} = \frac{-\frac{a}{Nb} [(\frac{c}{b} + 1 - \alpha)^2 + \alpha^2 N(1 - \alpha)]}{[(\frac{c}{b} + 1 - \alpha)^2 + \alpha^2 N \frac{c}{b}]^2} < 0 \quad (34)$$

For a given size of the stable coalition, the non-signatory countries increase their abatement when the cost decreases. Therefore, the signatory countries, which take into account the response from the non-signatory countries, will relax their optimal level of abatement as the cost of pollution abatement declines. It is important to emphasize that these results rely on a given size of the stable coalition.

A decreasing cost of pollution abatement will eventually alter the size of the stable coalition, which again affect the optimal levels of abatement. This will be analyzed further in the following chapter.

4.2 Expansion of the Stable Coalition

When the enthusiastic country, which will be a member of the coalition, invests in a technology that lowers the cost of abatement for all countries, the size of the stable coalition will eventually increase, meaning that $\partial \alpha / \partial c \leq 0$. The lower the cost of abatement, the larger is the stable coalition, all other parameter values equal. When analyzing how the optimal levels of abatement are affected when the cost of abatement decreases, the fact that the stable size of the coalition is altered should also be included.

4.2.1 Signatory Countries

The optimal level of abatement in the coalition is

$$Q_s(c, \alpha(c)) = \frac{\frac{a\alpha(c)^2 Nc}{b}}{\left[(\frac{c}{b} + 1 - \alpha(c))^2 + \frac{\alpha(c)^2 Nc}{b} \right]} \quad (35)$$

Including the effect of the cost-parameter c on the size of the stable coalition α ; $\partial\alpha/\partial c \leq 0$, the total effect on the coalition's optimal level of abatement of a lower cost of abatement is:

$$\frac{\partial Q_s}{\partial c} = \left\{ \frac{\left(\frac{2a\alpha Nc}{b} \frac{\partial\alpha}{\partial c} + \frac{a\alpha^2 N}{b} \right) \left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 Nc}{b} \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 Nc}{b} \right]^2} - \frac{\frac{a\alpha^2 Nc}{b} \left[2\left(\frac{c}{b} + 1 - \alpha \right) \left(\frac{1}{b} - \frac{\partial\alpha}{\partial c} \right) + \frac{2\alpha Nc}{b} \frac{\partial\alpha}{\partial c} + \frac{\alpha^2 N}{b} \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 Nc}{b} \right]^2} \right\} \quad (36)$$

The result is ambiguous and depends on if the cost decreases sufficiently to expand the stable coalition. As shown in chapter 4.1.3, the optimal level of pollution abatement for the coalition is reduced when the cost of abatement declines, as long as the size of the stable coalition remains unchanged, because the optimal level of abatement for the non-signatory countries increase as the cost decreases, for a given size of the stable coalition. However, as the cost declines sufficiently to increasing the stable coalition, the optimal level of abatement for the coalition will increase, both because there will be a larger number of signatory countries, and because every signatory country will increase the level of pollution abatement when the stable coalition expands.

Looking at a single signatory country, where the optimal abatement-level is:

$$q_s(c, \alpha(c)) = \frac{\frac{a\alpha(c)c}{b}}{\left[\left(\frac{c}{b} + 1 - \alpha(c) \right)^2 + \frac{\alpha(c)^2 Nc}{b} \right]} \quad (37)$$

the derivative of equation (37) with respect to c is:

$$\frac{\partial q_s}{\partial c} = \left\{ \frac{\left(\frac{ac}{b} \frac{\partial\alpha}{\partial c} + \frac{a\alpha}{b} \right) \left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 Nc}{b} \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 Nc}{b} \right]^2} - \frac{\frac{a\alpha c}{b} \left[2\left(\frac{c}{b} + 1 - \alpha \right) \left(\frac{1}{b} - \frac{\partial\alpha}{\partial c} \right) + \frac{2\alpha Nc}{b} \frac{\partial\alpha}{\partial c} + \frac{\alpha^2 N}{b} \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \frac{\alpha^2 Nc}{b} \right]^2} \right\} \quad (38)$$

Again, the result is ambiguous. The intuition is that as long as the cost of abatement declines to a level that does not alter the size of the stable coalition,

the optimal level of abatement for a signatory country will decrease when the cost of abatement decreases. As shown in the previous chapter, this is because the non-signatory countries will increase their level of abatement as the cost declines, as long as it does not alter the size of the stable coalition. However, if the cost decreases sufficiently to expanding the stable coalition, the optimal level of pollution abatement for every single signatory country will increase. This will be shown in the numerical analysis in chapter 4.3.

4.2.2 Non-Signatory Countries

As shown in chapter 4.1.3, the optimal level of pollution abatement for the non-signatory countries increases as the cost of abatement declines for a given size of the coalition. Now, including the effect of that the size of the coalition eventually changes as the cost of abatement changes, this effect must be included in the calculations by letting α depend on c , with $\partial\alpha/\partial c \leq 0$. Looking at the non-signatory countries, with:

$$Q_n(c, \alpha(c)) = \frac{a(1 - \alpha(c))(\frac{c}{b} + 1 - \alpha(c))}{(\frac{c}{b} + 1 - \alpha(c))^2 + \frac{\alpha(c)^2 N c}{b}} \quad (39)$$

the derivative of Q_n with respect to c , is:

$$\begin{aligned} \frac{\partial Q_n}{\partial c} = & \left\{ \frac{a \left[\left(-\frac{\partial \alpha}{\partial c} \left(\frac{c}{b} + 1 - \alpha \right) + (1 - \alpha) \left(\frac{1}{b} - \frac{\partial \alpha}{\partial c} \right) \right) \left(\left(\frac{c}{b} + 1 - \alpha \right)^2 + \alpha^2 N \frac{c}{b} \right) \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \alpha^2 N \frac{c}{b} \right]^2} \right. \\ & \left. \frac{-a(1 - \alpha) \left(\frac{c}{b} + 1 - \alpha \right) \left[2 \left(\frac{c}{b} + 1 - \alpha \right) \left(\frac{1}{b} - \frac{\partial \alpha}{\partial c} \right) + \frac{2\alpha N c}{b} \frac{\partial \alpha}{\partial c} + \frac{\alpha^2 N}{b} \right]}{\left[\left(\frac{c}{b} + 1 - \alpha \right)^2 + \alpha^2 N \frac{c}{b} \right]^2} \right\} \end{aligned} \quad (40)$$

It does, however, make more sense to look at how a single non-signatory country will react to a change in the cost of pollution abatement, since the self-enforcing coalition will eventually expand when the cost of abatement decreases, and the number of non-signatory countries will be lower.

For an individual non-signatory country, with an abatement-level equal to:

$$q_n(c, \alpha(c)) = \frac{\frac{a}{N}(\frac{c}{b} + 1 - \alpha(c))}{(\frac{c}{b} + 1 - \alpha(c))^2 + \frac{\alpha(c)^2 N c}{b}} \quad (41)$$

the result is the following:

$$\frac{\partial q_n}{\partial c} = \frac{\frac{a}{N} \frac{\partial \alpha}{\partial c} (\frac{c}{b} + 1 - \alpha)^2 - \frac{a \alpha c}{b} [\alpha \frac{\partial \alpha}{\partial c} + 2(\frac{c}{b} + 1 - \alpha)]}{[(\frac{c}{b} + 1 - \alpha)^2 + \alpha^2 N \frac{c}{b}]^2} \quad (42)$$

Also here, the result is ambiguous and depends on if the cost decreases sufficiently to altering the size of the stable coalition. However, as will be elaborated further in the subsequent chapter, the optimal level of abatement of a non-signatory country will increase as the cost decreases, as long as the stable size of the coalition remains unchanged. Furthermore, when the cost of pollution abatement decreases sufficiently to increasing the size of the stable coalition, the optimal level of abatement of the remaining non-signatory countries will decrease.

In this chapter I have shown how the signatory- and non-signatory countries will respond to a change in the abatement cost, taking into account that the stable coalition size will be altered as the abatement cost changes. In the next chapter I will consider a numerical example, developing Barrett's (1994) original calculations further, before continuing with the investment decision the enthusiastic country faces.

4.3 Numerical Analysis, Part 2

The stable size of the coalition increases when the cost-parameter, c , decreases. In the numerical calculations below, the numerical results, outlined in chapter 3.4, are further developed. I have used Barrett's (1994) parameter values as a point of departure, with $a = 100$, $b = 1$, and the number of countries, $N = 10$. However, I have tested how the game evolves with a lower cost-parameter, c . I have only looked at the effects of discrete changes in c , so the point at which the stable coalition increases might, and probably will, be at some values in

c	α	q_s	q_n	Q_s	Q_n	Q	π_s	π_n	Π
0,25	0,4	8,909	7,572	35,63	45,43	81,07	472,16	474,91	4738,12
0,24	0,4	8,811	7,709	35,24	46,26	81,50	473,57	475,75	4748,78
0,23	0,4	8,705	7,853	34,82	47,12	81,94	474,97	476,60	4759,47
0,22	0,4	8,590	8,005	34,36	48,03	82,39	476,38	477,45	4770,18
0,21	0,5	10,203	6,899	51,02	34,50	85,51	478,57	484,51	4815,40
0,20	0,5	10,101	7,071	50,51	35,35	85,86	479,80	485,00	4824,00
0,19	0,5	9,988	7,255	49,94	36,27	86,22	481,02	485,50	4832,61
0,18	0,5	9,864	7,453	49,32	37,26	86,58	482,24	486,00	4841,24
0,17	0,5	9,727	7,667	48,63	38,33	86,97	483,46	486,51	4849,88
0,16	0,5	9,574	7,899	47,87	39,49	87,36	484,68	487,02	4858,53
0,15	0,5	9,404	8,150	47,02	40,75	87,77	485,89	487,54	4867,19
0,14	0,5	9,215	8,425	46,08	42,13	88,20	487,10	488,07	4875,86
0,13	0,6	10,415	7,077	62,49	28,31	90,80	488,72	492,51	4902,35
0,12	0,6	10,251	7,403	61,50	29,61	91,12	489,75	492,77	4909,56
0,11	0,6	10,059	7,773	60,36	31,09	91,45	490,78	493,02	4916,76
0,10	0,6	9,836	8,197	59,02	32,79	91,80	491,80	493,28	4923,95
0,09	0,6	9,573	8,686	57,44	34,75	92,18	492,82	493,55	4931,12
0,08	0,7	10,440	7,084	73,08	21,25	94,33	494,03	496,39	4947,40
0,07	0,7	10,210	7,710	71,47	23,13	94,60	494,89	496,46	4953,65
0,06	0,7	9,915	8,499	69,41	25,50	94,90	495,75	496,53	4959,85
0,05	0,8	10,458	6,536	83,66	13,07	96,73	496,73	498,40	4970,65
0,04	0,8	10,204	7,653	81,63	15,31	96,94	497,45	498,36	4976,31
0,03	0,8	9,800	9,392	78,40	18,78	97,18	498,16	498,28	4981,86
0,02	0,9	10,204	6,803	91,84	6,80	98,64	498,87	499,44	4989,24
0,01	1	9,990	0,000	99,90	0,00	99,90	499,50	-	4995,00
0,00	1	10,000	0,000	100,00	0,00	100,00	500,00	-	5000,00

Table 4: The table shows the relationship between the cost of abatement, the stable coalition size and the respective optimal abatement and welfare levels.

between the values I have considered. This is, however, not important for the results.

Table 4 shows the relationship between the cost of abatement and the stable coalition size. Furthermore, it shows how the level of abatement in the signatory and non-signatory countries, as well as the total abatement, change as the cost changes. It also expresses how the welfare in the respective countries and the total welfare depend on c .

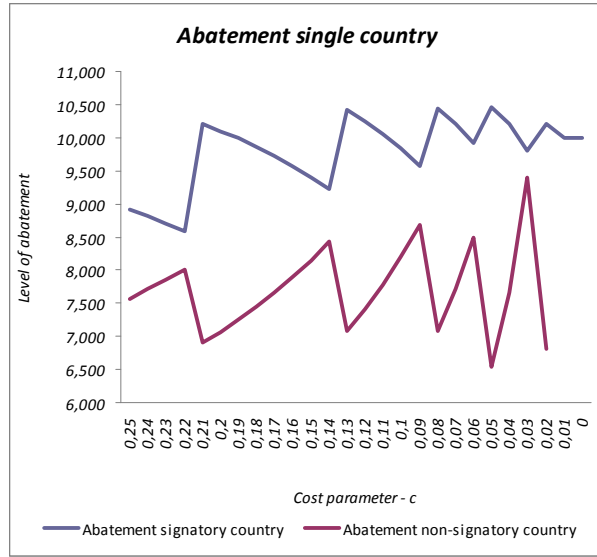


Figure 3: The development in the optimal level of abatement for a single signatory and non-signatory country as the cost of abatement, $c \rightarrow 0$.

From table 4, we can read that to increase the stable size of the coalition from consisting of four signatory countries to five, the cost of abatement must decrease from $c \in \{0, 25, 0, 22\}$ to $c \in \{0, 21, 0, 14\}$. A further increase in the stable coalition to consisting of six countries requires the abatement cost to drop to $c \in \{0, 13, 0, 09\}$, and so on. To reach a stable full cooperative outcome, $\alpha = 1$, the cost of abatement must be reduced to $c = 0.01$.

Looking at a single signatory country, the optimal abatement level, q_s , declines when c decreases, as long as the stable size of the coalition remains

unchanged, as shown analytically in chapter 4.1.3. The reason behind this result is that the non-signatory countries increase their level of abatement when the cost decreases for a given size of the stable coalition. When the cost of abatement declines enough to expanding the stable coalition size with one country, the optimal level of abatement for a single signatory country increases. As c declines further, the optimal abatement level for a signatory country decreases towards the point where the stable coalition again expands to consisting of an additional country. This pattern explains the ambiguity in the partial derivatives in chapter 4.2.1 and 4.2.2, and is shown graphically in figure 3.

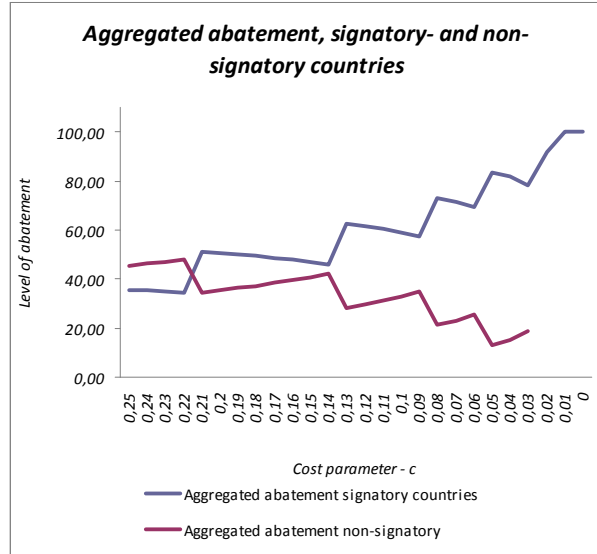


Figure 4: The figure shows the relationship between the optimal aggregated abatement level for the coalition and the non-signatories as the cost of abatement declines.

For instance, we see from table 4, that for $c = 0,21$ and $\alpha = 0,5$, which is the highest value of the cost-parameter that gives a stable coalition of five countries, the optimal level of abatement for a single signatory country is $q_s = 10,203$. As c declines from $c = 0,21$ to $c = 0,13$, which is the highest cost of abatement that gives a stable coalition consisting of six countries, $\alpha = 0,6$, the optimal abatement level increases to $q_s = 10,415$. This pattern continues as c declines and the size of the stable coalition, α , rises.

A similar pattern is found when looking at the optimal aggregated abatement of the signatory countries, Q_s , as pictured in figure 4. Clearly, as the stable coalition expands, the number of signatory countries increases, and thus aggregate pollution abatement will increase as c decreases every time an additional country enters the coalition.

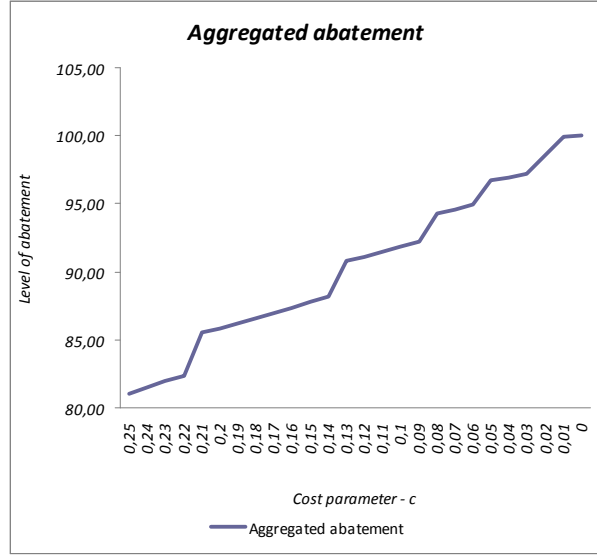


Figure 5: Aggregated level of abatement as a function of the cost-parameter, c .

Considering the non-signatory countries' optimal level of abatement, the pattern is the opposite. From table 4 we see that the optimal level of abatement for a single non-signatory country increases as the cost of abatement, c , declines for a given size of the coalition, as shown analytically in chapter 4.1.3. When the cost of pollution abatement declines to a level that triggers the stable coalition size to increase, the optimal level of abatement for the remaining non-signatory countries decreases, for so to increase as the cost declines towards the level at which the coalition again expands. These results explain the ambiguity in the analytical outcome in chapter 4.2.2. The abatement undertaken by a single non-signatory country follows the pattern in figure 3 as the cost-parameter, c , declines.

Clearly, as the size of the coalition becomes larger, the number of non-signatory countries declines. The aggregated level of pollution abatement in

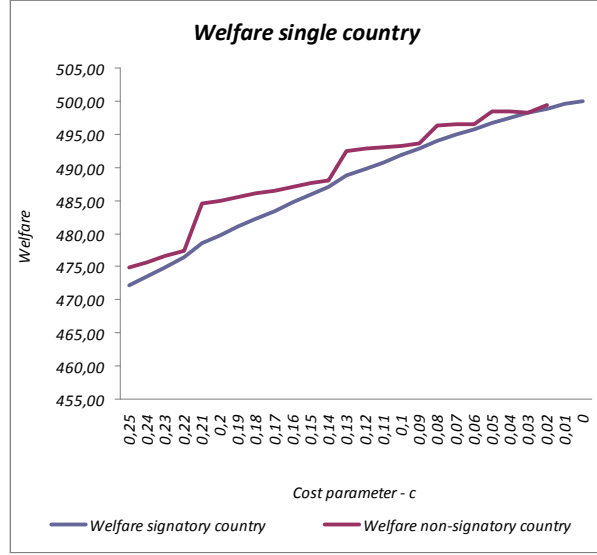


Figure 6: The development in the level of welfare in the respective type of countries as the cost of abatement declines.

the non-signatory countries, Q_n , is thus reduced every time one of the non-signatories enters the coalition and α increases, as shown graphically in figure 4.

The total level of pollution abatement in these ten countries increases steadily as the cost of abatement declines. As indicated in figure 5, the aggregated level of abatement increases evenly as the cost declines as long as the stable size of the coalition remains unchanged. When the stable coalition expands, there is a leap in the optimal total level of abatement, before it increases evenly towards where the stable size of the coalition again is expanded.

Regarding the development in the welfare level in the respective countries, both the welfare in the signatory and non-signatory countries, π_s and π_n , will increase as the cost of abatement decreases and the stable coalition expands, as pictured in figure 6. Clearly, as shown in figure 7, also the aggregated welfare, Π , will increase as the cost of pollution abatement becomes lower.

To achieve a lower cost of pollution abatement, one or more countries must be able or willing to invest in R&D such that the abatement technology improves,

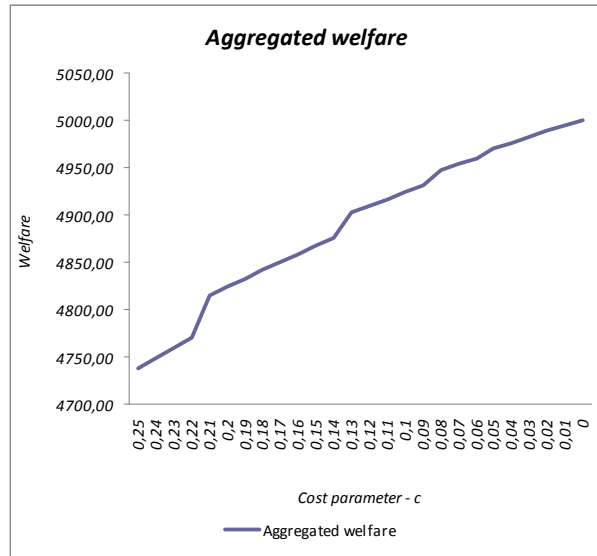


Figure 7: The total welfare increases as the cost of abatement declines.

and the cost of abatement declines for all countries. Also, this technology must be diffused to and implemented by the other countries. Given that the technology is diffused and implemented, and assuming that the "enthusiastic country" invests in R&D - how much will the enthusiastic country invest? I will look into this in the next chapter.

5 Investments

Lowering the cost of pollution abatement requires investments in R&D. It is relatively cheap to invent a technology that lowers the cost of abatement marginally. However, inventing breakthrough technologies, such as CCS, carbon sequestration, or highly efficient batteries that can be implemented in, for instance, the transport sector, requires far greater amounts of investments.

5.1 The Investment Function

The more the enthusiastic country is able and willing to invest, the lower will be the cost of pollution abatement, c . However, the marginal investment cost is increasing as $c \rightarrow 0$, meaning that the more the enthusiastic country invests, the more it has to invest to lower the cost of abatement by one more unit. The investment function, $I(c)$, is hence such that $I'(c) < 0$, and $I''(c) > 0$, and $I(0) = \infty$. A simple explicit function that satisfies these conditions is

$$I(c) = \frac{1}{c} \quad (43)$$

with

$$I'(c) = -\frac{1}{c^2} < 0 \quad (44)$$

and

$$I''(c) = \frac{2}{c^3} > 0 \quad (45)$$

The investment function is illustrated in figure 8.

How much the country invests depends on the information structure of the game. The information structure reflects the response the enthusiastic country meets from the other countries by investing in a cost-reducing technology. The responses to a lower cost is thoroughly studied throughout this thesis. Also the relation between the cost of abatement and the stable coalition is explained in depth in earlier chapters. The information structure will be presented in the following chapter.

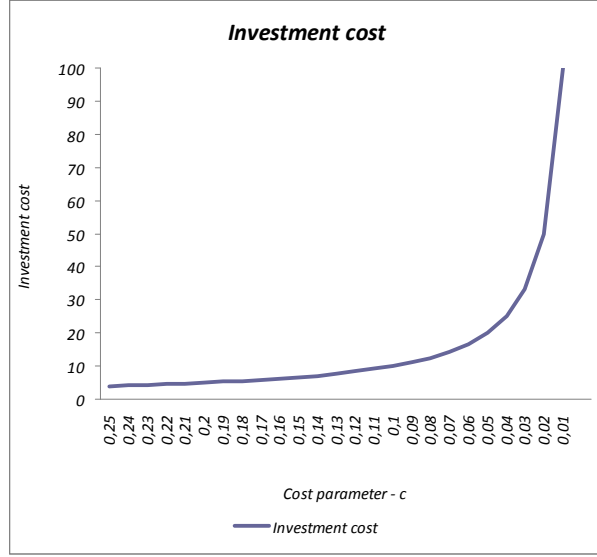


Figure 8: The investment cost is increasing as the cost-parameter $c \rightarrow 0$.

5.2 Information Structure

The terms *open-loop* and *closed-loop* specifies two types of information structures in multi-stage games. The open-loop, or non-strategic information structure characterizes a situation where the players choose their strategy based on calendar-time alone. Thus, the players do not take into account the response of the other players at the point where they make their decision. This type of information structure is appropriate for analyzing situations where the players, at the beginning of the game, do not observe any history other than their own. The closed-loop, or strategic information structure, on the other hand, describes a feedback strategy, where the players take into account the response of the other players when making their decision. The open-loop equilibrium is typically much easier to solve compared to the closed-loop equilibrium, since the closed-loop strategy space is much larger. The open-loop equilibrium can "serve as a useful benchmark for discussing the effects of strategic incentives in the closed-loop information structure, i.e., the incentives to change current play so as to influence the future play of opponents." (Fudenberg and Tirole, 1991, p. 130-131). In the model outlined in this thesis, the open-loop outcome is, in fact, hard to solve, and I will therefore focus mainly on the closed-loop cases.

When the enthusiastic country invests, in stage 0, and hence lowers the cost of abatement for all countries, several strategic effects should be taken into account. First, the optimal level of abatement for the enthusiastic country, which is one of the signatory countries, is altered. Second, the optimal level of abatement of the other signatory countries change. Furthermore, the optimal level of pollution abatement in the non-signatory countries are modified, as well as the size of the stable coalition.

There are thus several strategic effects that gives the enthusiastic country incentives to invest in R&D such that the cost of pollution abatement declines; The stable coalition is expanded, so more countries will sign the IEA and maximize aggregated net benefit, leading to a higher global welfare level. As we have seen, the investment might lead to lower abatement levels in the signatory countries, since non-signatories will increase their abatement level, given that the size of the stable coalition is not altered. This might be an extra incentive for the enthusiastic country to invest more than just what is needed to increase the size of the stable coalition.

In the closed-loop information structure, solving the game by using backward induction, the enthusiastic country takes all these strategic feedback effects into account when making the investment decision.

5.3 Two Types of Investments

I will consider two types of investment strategies for the enthusiastic country. The term enthusiastic is, as explained earlier, just a notion of a country with a larger historical focus on educational policies. The two types of investment strategies I will look at are one where the enthusiastic country invests "selfishly", and another where it invests "altruistically". The difference between these is the choice of which objective function to maximize when making the investment decision. When investing selfishly, the enthusiastic country maximizes it's own net benefit of the investment, while in the altruistic case, the enthusiastic country maximizes global welfare when making the investment decision.

5.3.1 Selfish Investment - Closed-Loop

An enthusiastic country that behaves selfishly, invests to maximize its own pay-off of the investment, taking into account the response to this investment by the signatory- and non-signatory countries, as well as the fact that the stable coalition expands as c decreases. Since the enthusiastic country at this point knows that it will be a signatory to the IEA, the optimal investment is found by solving the following maximization problem:

$$\max_c \{\pi_s^e = \pi_s - I(c)\} \quad (46)$$

The solution, taking into account the feedback this meets from the remaining countries, gives the optimal investments in R&D leading to the development of a technology that reduces the cost of abatement to c^* . The results are analyzed numerically in chapter 5.4.

5.3.2 Altruistic Investment - Closed-Loop

Suppose now, that the country with the possibility of investing plays altruistically, so as to maximize global welfare of the investment, rather than its own. The country will hence make the investment decision by solving the below maximization problem:

$$\max_c \Pi(c) = (\alpha(c) - 0, 1)\pi_s(c) + \pi_s^e(c) + (1 - \alpha(c))\pi_n(c) \quad (47)$$

which will give higher investments in R&D and a significantly lower optimal cost of pollution abatement, c^{**} .

5.3.3 Open-Loop Information Structure

The open-loop information structure can be regarded as a benchmark to emphasize the importance of the strategic feedback effects when developing national policies in a global setting.

Say that the enthusiastic country knew its optimal level of pollution abatement, both if investing selfishly and when investing altruistically. Let this level

be q_s^* , which corresponds to the optimal abatement level in the closed-loop information structure. If investing so as to minimize its costs to reach this level of abatement, without taking into account the feedback effects from the remaining countries, the enthusiastic country would minimize the aggregated cost of pollution abatement and the investment cost according to the following minimization problem:

$$\min_c \left\{ \frac{cq_s^{*2}}{2} + \frac{1}{c} \right\} \quad (48)$$

The first order condition, giving the optimal cost of pollution abatement is thus:

$$c = \frac{\sqrt{2}}{q_s^*} \quad (49)$$

This leads to a level of investment in R&D that is lower than the optimal investment level in the closed-loop information structure, both in the case of investing selfishly, and when investing altruistically. The cost-parameter c thus turns out to be higher than the optimal cost-parameter in the two closed-loop cases above. Hence, we have that the realized outcome, with respect to the level of abatement and the stable size of the coalition, is lower than in the closed-loop case. This fact makes the open-loop solution hard to find.

Investing so as to reach the optimal level of abatement nationally, will thus not lead to the same results as when taking into account the strategic feedback effects that are included in the closed-loop cases. Disregarding the strategic effects of national policies in an international setting will therefore not lead to optimal decisions, and the investing country would have chosen to invest more if given the possibility *ex-post*.

When facing an international challenge like global warming, it is therefore important that every individual country takes into account the strategic effects of national actions when designing their climate policies.

In the numerical analysis below, only the closed-loop information structure will be considered.

5.4 Numerical Analysis, Part 3.

By investing in a technology that reduces the cost of pollution abatement for all countries, the cost-benefit ratio, $\frac{c}{b}$, declines, and the difference in net benefits of pollution abatement between the non-cooperative and full-cooperative outcome becomes smaller. The IEA will then achieve a higher degree of cooperation, since the incentives to free-riding becomes lower, as stated in Barrett (1994).

The selfish and altruistic investment decisions lead to different optimal levels of investment, and thus to different optimal costs of pollution abatement. The situation is approaching the full cooperative outcome as c declines. It will, however, in neither case be optimal to invest such that the first-best solution is reached, where all countries sign the agreement.

Here, I will analyze the two outcomes numerically, starting with the case where the enthusiastic country invests "selfishly".

5.4.1 Selfish Investment

The welfare of the enthusiastic country is defined as $\pi_s^e = \pi_s - I(c)$. Inserting for the parameter values, we see from table 5 that the enthusiastic country's welfare level is increasing in the interval $c = \{0, 24, 0, 1\}$, and decreasing thereafter, as c declines towards zero. This is also showed graphically in figure 9. The optimal decision for the selfish enthusiastic country is thus to invest to maximize its payoff with regards to c . The enthusiastic country will therefore invest such that the cost of abatement declines to $c = 0, 1$. The corresponding welfare level for the enthusiastic country is then $\pi_s^e = 481, 80$, which is higher compared to the case without investments; $\pi_s(\alpha = 0, 4, c = 0, 25) = 472, 16$. The welfare in the remaining countries will be $\pi_s = 491, 80$ and $\pi_n = 493, 28$. The investment thus leads to a Pareto-improvement, since all countries' welfare levels increase as a result of the lower cost of mitigating pollution.

The investment will lead to an expansion of the stable coalition from consisting of four to six countries. The enthusiastic country will, furthermore, invest more than what is necessary to achieve a stable coalition of six countries. As shown in table 4, the highest cost of abatement leading to a stable coalition of six

\mathbf{c}	α	$\mathbf{I(c)}$	π_s^e	$\mathbf{\Pi}$
0,25	0,4	0,00	472,16	4738,12
0,24	0,4	4,17	469,40	4744,62
0,23	0,4	4,35	470,63	4755,12
0,22	0,4	4,55	471,83	4765,63
0,21	0,5	4,76	473,81	4810,64
0,20	0,5	5,00	474,80	4819,00
0,19	0,5	5,26	475,76	4827,35
0,18	0,5	5,56	476,69	4835,68
0,17	0,5	5,88	477,58	4843,99
0,16	0,5	6,25	478,43	4852,28
0,15	0,5	6,67	479,23	4860,52
0,14	0,5	7,14	479,96	4868,72
0,13	0,6	7,69	481,02	4894,66
0,12	0,6	8,33	481,42	4901,23
0,11	0,6	9,09	481,69	4907,67
0,10	0,6	10,00	481,80	4913,95
0,09	0,6	11,11	481,71	4920,01
0,08	0,7	12,50	481,53	4934,90
0,07	0,7	14,29	480,61	4939,37
0,06	0,7	16,67	479,08	4943,19
0,05	0,8	20,00	476,73	4950,65
0,04	0,8	25,00	472,45	4951,31
0,03	0,8	33,33	464,83	4948,53
0,02	0,9	50,00	448,87	4939,24
0,01	1	100,00	399,50	4895,00
0,00	1	∞	—	—

Table 5: The table shows the development in the welfare level of the enthusiastic country, and the global welfare level, taken into account the investment cost.

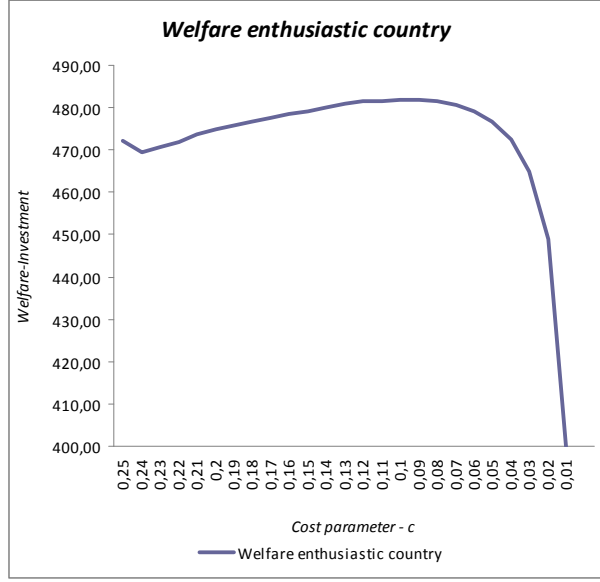


Figure 9: The welfare of the enthusiastic country as the cost-parameter, $c \rightarrow 0$.

countries is $c = 0,13$. The enthusiastic country has an incentive to invest more than what is necessary to obtain a stable coalition of six countries, since the optimal level of abatement for the non-signatory countries increase as the cost declines for a given size of the stable coalition. The enthusiastic country, along with the rest of the signatory countries, can thus relax their level of abatement slightly by investing so that the cost is $c = 0,10$ rather than $0,13$.

Regarding the level of pollution abatement, the investment will lead to an aggregated level equal to $Q(\alpha = 0,6, c = 0,10) = 91,80$, which is significantly higher than the level of abatement in the self-enforcing coalition without investments, $Q(\alpha = 0,4, c = 0,25) = 81,07$. The results can be found in table 4. This is due to two effects: First, every single country will increase the level of abatement when the cost declines sufficiently, and, second, the stable coalition will increase, and more countries will maximize joint welfare rather than their individual net benefits of pollution abatement.

Since the enthusiastic country also benefits from the investment in R&D, it does not need to have a "moral obligation" to be willing to do so. If this country had a moral obligation to invest to "save for all", it would invest more

than what maximized this country's own net benefit. In this case global welfare would increase further, but on the cost of the enthusiastic country's own welfare. Such an altruistic investment will be elaborated below.

5.4.2 Altruistic Investment

In the altruistic case, the enthusiastic country invests to maximize global welfare according to equation (47). This case lies closer to what can be regarded as a moral obligation to "save for all", since the enthusiastic country invests more than what maximizes its own net benefits. Numerically, this generates the result outlined in table 5, and is shown graphically in figure 10. The global welfare is maximized when the cost of abatement is equal to $c^{**} = 0,04$, which expands the stable coalition to consisting of eight countries, $\alpha = 0,8$.

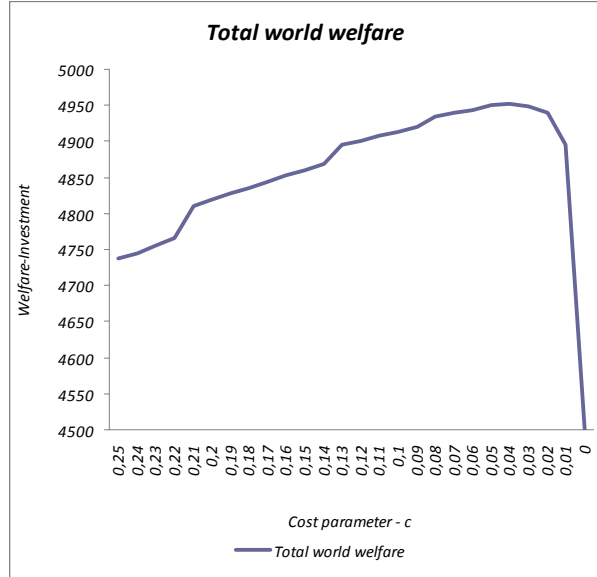


Figure 10: The global welfare, taken into account the investment cost, is maximized when the cost-parameter is equal to $c = 0,04$.

Considering the enthusiastic country's welfare, it will still be greater than in the initial situation, without any investments, although just marginally greater.

An investment lowering the cost of pollution abatement to $c = 0,04$ leads to a net-benefit in the enthusiastic country equal to $\pi_s^e(\alpha = 0,8, c = 0,04) = 472,45$, while without the investment it would have been $\pi_s(\alpha = 0,4, c = 0,25) = 472,16$. The welfare level in the other countries will, furthermore, rise accordingly to $\pi_s = 497,45$ and $\pi_n = 498,36$. Also here, for the same reasons as in the previous case, the country will invest more than necessary to reaching a stable coalition consisting of eight countries. Investing to maximize the global welfare thus also leads to a Pareto improvement compared to the initial situation without investments.

The level of abatement will as a result of the altruistic investment increase from $Q(\alpha = 0,4, c = 0,25) = 81,07$ to $Q(\alpha = 0,8, c = 0,04) = 96,4$, which is close to the full cooperative outcome without investments.

These two cases, show the importance of the strategic effects of the investment. When the cost declines, and the stable coalition expands, the optimal abatement level in all countries increases. This affects the benefit of the enthusiastic country positively.

6 Conclusions

In this thesis I have examined the role of strategic technology development for the outcome of International Environmental Agreements (IEAs), and the incentives to make such investments. The analysis is based on a quadratic cost-benefit model introduced by Barrett (1994). I have extended this model to including investments in R&D by a single "enthusiastic" country, such that the cost of pollution abatement is reduced globally. The model has, as in Barrett (1994), been solved numerically for ten countries, which can also be regarded as ten world regions.

I have not evaluated the realism of the chosen investment function. It may be that the chosen function yields more optimistic results than what is realistic, and that this leads to conclusions that might reflect a certain "technology optimism". The important is, however, the mechanisms, which are thoroughly evaluated throughout this thesis.

The literature on self-enforcing IEAs gives a rather grim picture of the possibilities for solving the climate challenge. The reason behind this is that when the gains to cooperation are substantial, the incentive to free-ride is large, resulting in low participation in IEAs. Conversely, when the difference in net-benefits between the non-cooperative and full cooperative outcome is small, cooperation is relatively easy to achieve. The challenges the world faces today with regards to the climate, is a situation where the gains to cooperation are large.

The fact that the higher the net benefits are from constructing an IEA, the lower is the participation level, is not necessarily a problem - it also creates possibilities. This is where investments in R&D to develop cost-reducing abatement technologies plays a main role. If a country can impact the cost-benefit ratio through investing in a technology that lowers the costs of pollution abatement for all countries, the situation is improved through two mechanisms: First, since the cost of mitigating pollution is reduced, more abatement will be undertaken, and second, since the difference in net-benefits in the non-cooperative and full cooperative outcome becomes lower, the incentive to free-ride is lower, and more nations will participate in the climate coalition. There is thus a double dividend from investing in R&D to develop cost-reducing technologies.

In this thesis the focus has been on a frontrunner country, which I have called the "enthusiastic" country. This country is characterized by having a higher level of human capital, and thus lower costs of developing a cost-reducing abatement technology, compared to the remaining countries. I have analyzed two types of investments: one where the enthusiastic country invests selfishly, so as to maximize its own net benefits of the investment, and another, where the country invests altruistically, maximizing the world's net benefit of the investment. The first best, meaning full cooperation, will not be achieved in either case. The investment will, however, pay off in an expanding stable coalition, and all countries, including the enthusiastic country, will earn higher welfare levels compared to the *ex-ante* situation in both the selfish and the altruistic case. The investment thus leads to a Pareto improvement in both cases, meaning that if a country has the possibility to invest in such technology, it should and will actually do so. A selfish investment will increase the welfare in the enthusiastic country, and also lead to increased welfare globally. The altruistic investment yields greater achievements globally, but will only lead to a marginal increase in welfare for the enthusiastic country, due to higher investment costs.

Although the model developed throughout this thesis is rather simplistic, it captures the idea that investments in R&D to develop cost-reducing abatement technologies can be a possible, and even necessary, approach to both increasing participation in IEAs and to increase mitigation of GHGs. The rather grim results in the literature on self-enforcing IEAs, concluding that stable coalitions typically consist of a relatively small number of countries, is thus altered when introducing the possibility of investments such that the cost of abatement declines for all countries. Also, the model reflects the importance of strategic investment policies. A country should, when making the investment decision, take into account the strategic effects this technology has on the abatement decision in all other countries.

As we have seen, the stable size of the coalition depends critically on the parameter values. To increase the level of mitigation activities, targets and timetables, which is the main focus in the current climate negotiations, may not be the appropriate tools, since it does not impact the size of the self-enforcing IEA. However, investing in R&D to develop cost-reducing mitigation technologies, will alter the size of the self-enforcing IEA, and thus increase both the participation and the level of abatement undertaken in both the signatory coun-

tries, and the singletons outside the coalition. To reach a successful outcome of future climate negotiations, the focus should thus be turned from targets and timetables to investments in developing cost-reducing abatement technologies, which will enhance both participation and mitigation activities.

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